EXPERIMENTAL INVESTIGATION OF THE CORRELATION OF DIRECT AND SPECULARLY REFLECTED WAVES

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The results of the experimental investigation of the effect of the correlation of the fields of direct and reflected beam in the radar scheme of the propagation of radiation through a randomly nonuniform medium on the variance of random displacements of the image are presented. It is shown that the "self-compensation" effect accompanying reflection of radiation from a 90-degree prism and the intensification of fluctuations accompanying reflection from a flat mirror depend on the separation of the beams axes.

In the radar schemes of propagation of light beams the correlation of the direct and reflected waves, passing through the same nonuniformities of the medium, results in qualitatively new phenomena and behavior which are not observed in the case of direct propagation.[1,2] However the question of the region of manifestation effects associated with the correlation of the direct and reflected waves when the optical axes of the transmitter and receiver are separated remains open, though such studies are important owing both to the widespread use of remote methods for determining the parameters of medium and the necessity of analyzing the reliability and accuracy of lidar systems[3] and the possibilities of model turbulent installations.[4]

In this work we studied experimentally the effect of spatial correlation of the direct and reflected waves on the variance of the displacements of the optical image under conditions of thermal, model, convective turbulence. Following Ref. 5, it can be shown that in the case when radiation from a source of plane waves ($\Omega = ka^2/z \gg 1$, where a is the radius of the radiating aperture of the source, $k = 2\pi/\lambda$ is the wave number, and z is the path length) propagates through a turbulent medium, the conditions for weak fluctuations of the intensity are satisfied along the path ($\beta_0^2 = 0.31C_\varepsilon^2 k^{7/6} z^{11/6} \ll 1$, C_ε^2 is the structure constant of the medium dielectric constant of the medium), and reflection occurs from a large flat or corner mirror reflector ($\Omega_r = ka_r^2/z \gg 1$, a_r is the effective radius of the reflector) the variance of random displacements of the image is equal to

$$\sigma_t^2 = \sigma_{dir}^2 + \sigma_{ref}^2 \pm \sigma_k^2, \tag{1}$$

where

$$\sigma_{dir}^2 = \frac{1}{2}\sigma_{t_0}^2\left\{1 + \mathrm{Re}\int_0^1 d\xi\,(1 + 2i\Omega_t^{-1}(2-\xi))^{-1/6}\right\}$$

is the variance of the image jitter along the source-reflector path,

$$\sigma_{ref}^2 = \frac{1}{2}\sigma_{t_0}^2\left\{1 + \mathrm{Re}\int_0^1 d\xi\,(1 + 2i\Omega_t^{-1})^{-1/6}\right\}$$

is the variance of the image jitter along the reflector-receiver path,

$$\sigma_k^2 = \sigma_{t_0}^2\,\mathrm{Re}\left\{(1 + 2i\Omega_t^{-1})^{-1/6} + \int_0^1 d\xi\,(1 + 2i\Omega_t^{-1}(1-\xi))^{-1/6}\right\}$$

is the variance of the image jitter owing to the correlation of .the waves propagating in the forward and backward directions,

$$\sigma_{t_0}^2 = \frac{\pi^2}{2} A_0 \Gamma(1/6) F_t^2 z C_\varepsilon^2 (a_t^2/2)^{-1/6}$$

is the variance of the jitter of the image of the plane-wave source on the direct path[6], and $\Omega_t = ka_t^2/z$ is the Fresnel number of the receiving lens with an effective radius a_t (in Eq. (1) the upper "plus" sign refers to the case of reflection from a flat mirror and the lower "minus" sign refers to the case of reflection from a corner reflector). From Eq. (1) with $\Omega_t \ll 1$ (reception with a large lens) it follows that[5,7,8]

$$\sigma_t^2 = 2\sigma_{t,f}^2\ (2z) = 4\sigma_{t_0}^2, \tag{2}$$

in the case of a flat mirror and

$$\sigma_t^2 \equiv 0 \tag{3}$$

in the case of a corner.

Thus in the case of reflection from a flat mirror correlation of the direct and reflected waves results in quadrupling of the variance of the image jitter as compared with the direct path, and in the case of reflection from a corner it results in complete compensation of the random displacements of the optical image. These results have a clear physical interpretation. It is well known[6] that random displacements of the image in the plane of the sharp image of the receiving lens are caused by random rotations of the phase front of the wave. If the extended source is replaced by an interferometer with a corresponding baseline, then the random rotations of the phase front of the wave will introduce phase differences $\Delta\varphi$ in the interferometer slits and the variance of the random displacements σ_a^2 will be proportional to $(\Delta\varphi)^2$. We shall find the phase difference for the points 1 and 2 (Fig. 1). In the case of direct propagation $\Delta\varphi = \varphi_1 - \varphi_2$, where φ_1 and φ_2 are, respectively, the increments to the phases for the points 1 and 2 after one pass over the path. In the case of double passage through the medium with strictly backward reflection the phase increment will be $2\varphi_1$ at the point 1 and $2\varphi_2$ at the point 2 when reflection occurs from a flat mirror and $\varphi_1 + \varphi_2$ at the point 1 and $\varphi_2 + \varphi_1$ at the point 2 when the reflection occurs from a corner. Then the phase difference is $2\varphi_1 - 2\varphi_2 = 2\Delta\varphi$, and the variance $\sigma_a^2 \sim 4(\Delta\varphi)^2$ in the case of a flat mirror and $(\varphi_1 + \varphi_2) - (\varphi_2 + \varphi_1) \equiv 0$, while the variance $\sigma_a^2 \equiv 0$ in the case of a corner.

It follows from expression (1) that decorrelation of the direct and reflected waves results in a decrease on reflection from a flat mirror and an increase on reflection from a corner mirror in the variance of the image jitter to a value determined by the sum of the variances of the image jitter along the "source-reflector" and "reflector-receiver" paths, i.e., to $\sigma_{dir}^2 + \sigma_{ref}^2$; in addition, the character of the specular reflection (i.e., the type of the mirror reflector) is insignificant.

The effect of separation of the axes of the direct and reflected beams on the mutual correlation of the beams was studied experimentally in a randomly nonuniform medium using a setup[9] that models the conditions of developed convective turbulence. The experimental arrangement is presented in Fig. 2. A collimated laser beam (λ = 0.63 μm), whose size a = 0.3 cm at the e^{-1} level and which passed twice .(before and after reflection) through a layer of the turbulent medium z = 2 m, was focused with an objective lens whose focal length F = 40 cm. The displacement of the center of gravity of the optical beam in two mutually perpendicular directions x and y in a plane perpendicular to the direction of propagation was measured using a search-and-tracking system built based on a dissector tube. The photocathode of the dissector was placed in the focal plane of the objective. The principle of operation of such devices is described in detail in Ref. 10. The variances of the displacement of the radar image σ_x^2 and σ_y^2 along the coordinate axes were determined simultaneously with a two-channel variance meter having a dynamic range of at least 40 dB. The averaging time for each realization was ~5 min. The measurements were performed with two types of reflectors: a flat mirror and a 90-degree prism. The prism rotates the field of the wave by 180° in a direction perpendicular to the principal edge of the prism. In the direction parallel to the principal edge of the prism as a reflector is identical to a flat mirror. The construction of the setup made it possible to change the height of the laser beam above a heated surface. The formation of a plane wave in the beam was guaranteed by satisfaction of the condition $ka^2/z \gg 1$. The experiment was performed under conditions of weak fluctuations of the intensity when random displacements of the center of gravity of the image were mainly determined by the angular wandering of the beam as a whole.

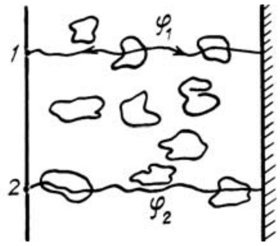

FIG. 1. Diagram illustrating the physical mechanism of the effect of the manual correlation of the direct and reflected waves.

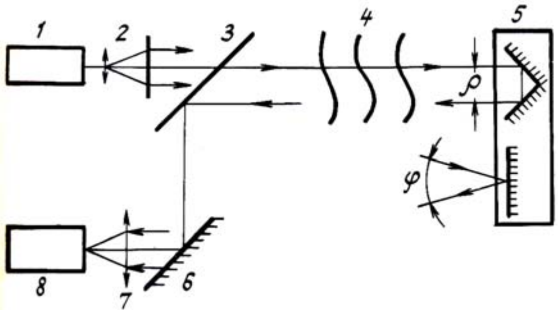

FIG. 2. Block diagram of the experimental arrangement: 1 – LG-38 laser; 2 – collimator; 3 – beam-splitting plate; 4 – layer of nonuniform medium; 5 – reflectors; 6 – mirror; 7 – receiving objective; 8 – tracking unit.

The degree of correlation of the direct and reflected waves in the case of reflection from a flat mirror was determined by the ratio of the variance of the fluctuations of the image of the source with the axes of the beams separated by an angle φ to the variance with φ = 0, and' in the case of reflection from a prism it was determined by the ratio of the variance of the fluctuations of the image along the x-axis as a function of the separation ρ of the axes of the beams in the horizontal plane to the variance of the fluctuations along the y-axis with ρ = 0. The edge of the prism wedge was placed parallel to the vertical y-axis.

Figure 3a shows the measurements of the spatial correlation of the lidar image in the case of reflection from a prism. The measurements were' performed above a heated surface at heights of 6 cm (curve 1), 14 cm (curve 2), and 22 cm (curve 3). For $\rho = 0$, when the axis of the direct and reflected beams coincides self-compensation occurs for horizontal displacements and the variance of the displacements σ_x^2 is minimum. When the axes are separated ($\rho > 0$) the wave fields are no longer correlated and the variance of the horizontal displacements increases as the separation increases. For each height the variance of the vertical displacements remains practically constant and equal to $4\sigma_{y,fl}^2$ within the limits of the separation of the beams $\rho \le 2a$. One can see from the figure that the residual level of the fluctuations with ρ = const and the rate at which the correlation of the wave fields decreases as p increases depend on the height of the beam above the heated surface. Those characteristics can be explained by the effect of the turbulent characteristics of the medium, i.e., it is well known[6,11] that in a convective flow the value of the structure constant of the refractive index C_n^2 decreases in proportion to $h^{-4/3}$ and the outer scale of turbulence L_0 is proportional to the height. It is also known[5] that the variance of the random displacements of a radar image depends on L_0. Analysis of the dependence $\sigma_t^2 \sim f(L_0)$ with large values of the outer scale of turbulence $(L_0^2 / a_t^2) > 1$ shows that in the case of a corner $\sigma_t^2 \sim (L_0^2 / a_t^2)^{-13/6}$. This explains the higher residual level of fluctuations with ρ = const at a height of 6 cm as compared with other heights (14 and 22 cm). For the same separation of the axes the effect of attenuation of the fluctuations vanishes most rapidly for beams at a height of 6 cm. On the linear section of the curves ($\rho < 2a$) the ratio $\sigma_x^2 / \sigma_{y_0}^2$ is proportional to $h^{1/2}$ to within 10%; this indicates that the degree of correlation depends on the value of the outer scale L_0.

When the beams are separated vertically (the edge of the prism is parallel to the horizontal axis) the degree of correlation of the random displacements of the lidar image was not observed to depend, within the limits of error of the measurements, on the propagation height of the beams.

Figure 3b shows the measurements of the ratio $\sigma_\varphi^2 / \sigma_0^2$ in the case of reflection of a beam from a flat mirror. The measurements were performed at a height of 14 cm. In the case of strictly backward reflection ($\varphi = 0$) the random displacements are quadrupled ($\sigma_{\alpha_0}^2 = \sigma_{\alpha,f}^2$); this effect vanishes as the angle φ is increased, and in our experiment for $\varphi \sim 10a/z$ the variance of the fluctuations of the center of gravity of the radar image was equal to the variance along the doubled path.

The experimental results presented in this paper show that even for $\beta_0^2 \ll 1$ and $\Omega \gg 1$ the effect of intensification (attenuation) of the displacements of the image of a source on the reflection from a flat mirror (prism reflector) decreases when the axes of the incident and reflected beams are separated, and it vanishes completely when the horizontal separation p is equal to the beam size $2a$ and when the angular separation $\varphi \ge 10a/z$.

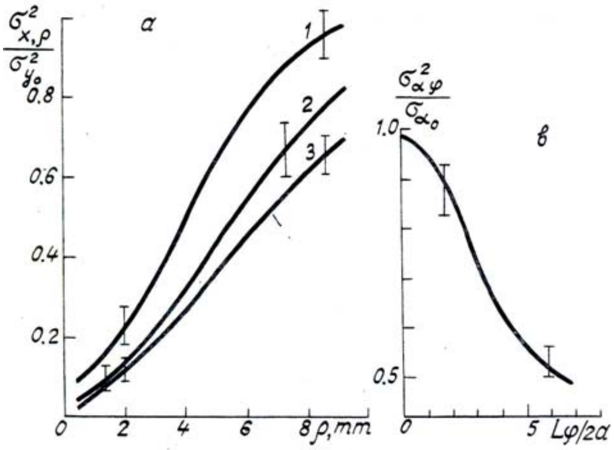

FIG. 3. The displacement of the lidar image of the source versus the separation of the axes with reflection from a prism (a) and with reflection from a flat mirror (b).

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